

Inner-shell ionization, radiative losses and thermal conductivity in young SNRs

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ABSTRACT

Self-consistent treatment of time-dependent ionization in hydrodynamical calculations of the X-ray emission from young supernova remnants has been performed. The novel feature of the calculations is that K_α lines from species produced by inner-shell collisional ionization are included. Parameters of the shocked ejecta are found from fitting the model spectrum to the observed one. The application of the method to Tycho SNR using the classical deflagration model W7 for the explosion enables us to well reproduce the observed X-ray spectra and radial brightness profiles of the remnant.

Key words: supernovae remnants - x-ray emission: time-dependent ionization - inner-shell ionization.

1 INTRODUCTION

The supernova remnant 1572 (Tycho SNR) is a convenient object for testing thermonuclear supernova models. The available observational data (Smith et al. 1988; Fink et al. 1994; Decourchelle et al. 2001; Warren et al. 2005) makes it possible to test both the theory of thermonuclear supernova explosions and gas-kinetic processes in plasma heated by the SN blast wave. Studies of Tycho SNR (Itoh et al. 1988; Brinkman et al. 1998; Sorokina et al. 2004; Badenes et al. 2003) showed that it is difficult to find a model which describes self-consistently its origin and evolution. Nevertheless, the increasingly accurate account for various physical processes in analyzing of SNR observations makes it possible to narrow the range of possible explosion mechanisms.

As was shown in detail in Sorokina et al. (2004) (hereafter Paper I), the accurate modeling of young SNRs even in one-dimensional hydro calculations requires taking into account radiative energy losses and self-consistent calculation of plasma ionization state in every mesh zone at every time step. In addition, such processes as thermal conductivity of electrons and non-Coulomb energy exchange between electrons and ions should be included. It is very hard to treat these processes from the first principles, so two free parameters have been introduced. The

values of these parameters can be found from comparison with observations. In Paper I we compared modeled emission with X-ray observations of Tycho SNR obtained by the XMM-Newton X-ray observatory and reported in Decourchelle et al. (2001). The data include X-ray (0.2–10 KeV) spectrum and azimuthally averaged profiles of X-ray brightness in silicon and iron lines (Fe XVII, Si K, Fe K).

In Paper I numerical simulations of SN ejecta propagated into the surrounding interstellar medium have been performed for two models: the parametric deflagration model **W7** (Nomoto et al. 1984), and new 3D (the “first principle”) model **mr0** elaborated in Max-Planck-Institute für Astrophysik (Reinecke et al. 2002). X-ray spectra and radial brightness profiles of the remnant expected at an age of 430 years (the age of Tycho SNR) were computed for these models. However, the comparison with the XMM observations revealed noticeable discrepancies. For example, in the W7 model, X-ray spectrum did not reveal the presence Fe K line and for no model the observed relative position of X-ray brightness profiles in silicon and iron lines was obtained. However, these disagreements could not be used to reject the models considered, since not all relevant physical processes were fully incorporated into the radiation hydro code at that time.

In later studies by Kosenko et al. (2005), an attempt to modify the initial density profile of the SN ejecta was done. The outermost layers of the ejecta were made more rarefied. These modifications showed that the density pro-

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file does not have a noticeable effect on the resulting X-ray brightness profiles of the remnant. However, a fine tuning of the parameters in the density distribution in the ejecta made it possible to well reproduce the observed radial brightness profiles. In that case most of the emission in silicon and iron lines should have been generated by the external SNR shock (not by the reverse shock), which seems rather unlikely (Hwang et al. 1998).

When calculating X-ray emission from the remnant in Paper I, we did not take into account inner-shell ionization processes from low-ionized elements. In stationary plasma, collisional production of K_α emission lines is suppressed due to a small value of the cross-section of interaction between free and inner-shell electrons. Usually K_α emission lines from low-ionization ions are produced via photoionization processes (fluorescence). In shocked plasma time-dependent ionization occurs and in a SNR the ionization time-scale is about several hundred years (Sorokina et al. 2004). Thus the matter behind the reverse shock front should be highly under-ionized compared to the temperature of ionizing electrons. Hence the collisional ionization of ions from inner-shells is highly operational in the emission line production in a SNR. In Vink et al. (2003) the role of inner-shell excitation processes to Si K_α feature was investigated in SN1006.

The main goal of this paper is to assess the role of inner-shell ionization processes in the X-ray emission of young supernova remnants. We calculate the hydrodynamic evolution and X-ray emission of a young remnant using the code SUPREMNA, introduced in Paper I, with inner-shell ionization processes taken into account. The example of the classical deflagration model W7 shows that it may produce the X-ray spectrum and radial brightness profiles very close to the ones observed from Tycho SNR for some set of parameters. In particular, the iron K_α line may be pronounced in this model without invoking additional mixing in the ejecta.

2 CALCULATION OF THE INNER-SHELL IONIZATION IN SNRS

To calculate the intensity of a line produced by ionization from the inner shell ($n = 1$) of an ion followed by the transition of an electron from level n to this vacant place, the following formula was employed (Spitzer 1978; Kallman et al. 2004)

$$\mathcal{J}_{n1}^i = n_i n_e \langle \sigma v \rangle_i \omega_{i,n1} E_{n1} \left[\frac{\text{erg}}{\text{cm}^3 \text{s}} \right] \quad (1)$$

where n_i , n_e are number densities of ions i and electrons correspondingly;

$$\langle \sigma v \rangle_i = \int_{E_{\text{thr}}[i]}^{\infty} \sigma v f(v) dv \quad (2)$$

is the velocity averaged cross-section. Here $E_{\text{thr}}[i]$ is the threshold ionization energy from the inner-shell of ion i , $f(v)$ is the Maxwellian distribution function for electrons; $\omega_{i,n1}$ is the fluorescence yield (photons/ionization) for the line which corrects the intensity for photonless

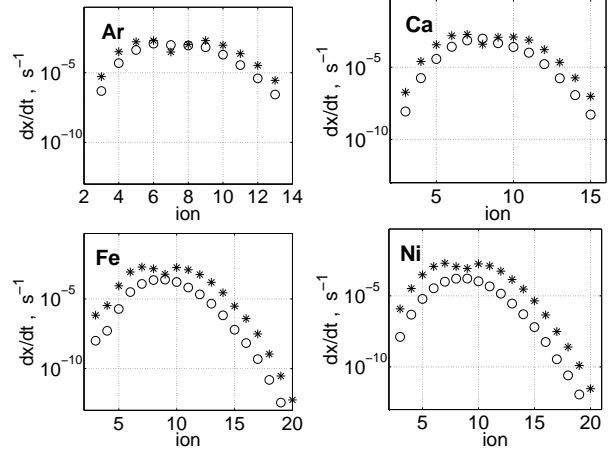


Figure 1. Ionization rates for Ar, Ca, Fe, Ni. Asterisks (“*”) show standard ionization rates used in SNR simulations. Circles (“o”) show the inner-shell ionization rates. Matter with an initial temperature of $T_{\text{in}} = 10^4$ K was instantly heated up to $T_{\text{fin}} = 2 \times 10^8$ K. The ionization parameter is $nt = 3 \times 10^9 \text{ s/cm}^3$.

transitions due to Auger electrons (Kaastra, Mewe 1993; Kallman et al. 2004); E_{n1} is the energy of the line.

Approximate formulas for the inner-shell ionization cross-sections σ were taken from Hombourger (1998). These formulas fit experimental data for a wide range of ions and electron energies. Each cross-section formula was convolved numerically with the Maxwellian velocity distribution (formula 2). For each species dependence $\langle \sigma v \rangle_i$ on temperature was numerically approximated with an accuracy of better than 1% and then inserted into the emission routine. Data on $E_{\text{thr}}[i]$, $\omega_{i,n1}$, E_{n1} was taken from Kaastra, Mewe (1993).

In the SNR modeling, the plasma ionization state is calculated by solving a system of kinetic equations in each grid mesh at every time step. Assuming that inner-shell ionization processes do not affect very much the electron production rate and thus the equation of state of the matter, the inner-shell ionization has not been included in the kinetic equations. Fig.1 shows ionization rates for some ions. Ionization rates which are included in the present paper (and in Paper I) are shown by asterisks “*”, the inner-shell ionization rates are presented by circles “o”. In most cases the inner-shell ionization rates are several times smaller than the standard (outer-shell) ionization rates.

We did not include inner-shell excitation processes in our method. Contribution of excitations from inner-shell is negligible compared to normal excitations and inner-shell ionization rates. For example, formulae from Mewe, Gronenschild (1981) show that the ratio of normal excitation rates to inner-shell ionization and to inner-shell excitation for Fe XXV at temperature $\sim 10^8$ K is about $1 : 0.5 : 10^{-4}$.

3 COMPARISON WITH OBSERVATIONS

The results of the calculations have been compared with the X-ray observations of Tycho SNR performed by XMM-Newton observatory. The data were taken from the public available library of the observatory¹. These observations were conducted with the EPIC instrument, the spectrum was extracted from data obtained by the MOS1 camera.

Based on W7 explosion model, eight variants of hydrodynamical calculations have been performed for different values of three parameters describing the thermal conductivity (C_{kill}), non-Coulomb energy exchange between electrons and ions (q) and the density of the circumstellar matter (ρ_{CSM}). Calculated spectra were converted to an XSPEC (Arnaud 1996) table model with these three interpolation parameters. The physical meaning of the parameters C_{kill} and q is as follows.

The factor $0 < C_{\text{kill}} < 1$ describes the fraction of the thermal flux contributed to the system compared to the standard case (formula (7) in Paper I), where the flux is limited only by the existence of a maximum speed (the speed of sound) for the heat carriers, ignoring a possible decrease in the particle mean free path due to magnetic fields and plasma instabilities. To describe the effects of collisionless energy exchange, in Paper I we introduced the parameter q that specifies the fraction of artificial viscosity Q , added to the pressure of ions: $P_i = P_i(\text{thermal}) + qQ$. Then for the electronic component we put $P_e = P_e(\text{thermal}) + (1 - q)Q$. If only the collisional exchange is taken into account, $q = 1$ and we used the standard system of equations with only ions heating of at the front.

Comparison of the spectra

By fitting the XSPEC table models to the XMM-Newton observations, we found the values of the table interpolation parameters. Then with these values a new hydrodynamical model was calculated. Fig.2 shows the observed spectrum (EPIC MOS1) and theoretical spectrum obtained for the W7 model. Table 1 lists the values of fitting parameters. The best-fitting values for the column density N_H is also shown in the table.

Inset in Fig.2 shows Fe K line profile in details. It is clear from the figure that modeled centroid shifted to higher energies, compared to observable one. This discrepancy indicates that the matter in our model is slightly overionized, thus the temperature or ionization timescale of the Tycho remnant should be lower. These arguments point to less energetic model for the remnant.

Comparison of the remnant's brightness profiles

Following the scheme elaborated in Paper I, the radial brightness profiles of the model remnant were constructed in Si K, Fe XVII, Fe K lines (Decourchelle et al. 2001). The results are plotted in Fig.3. The figure shows the X-ray brightness profiles for W7 model, calculated

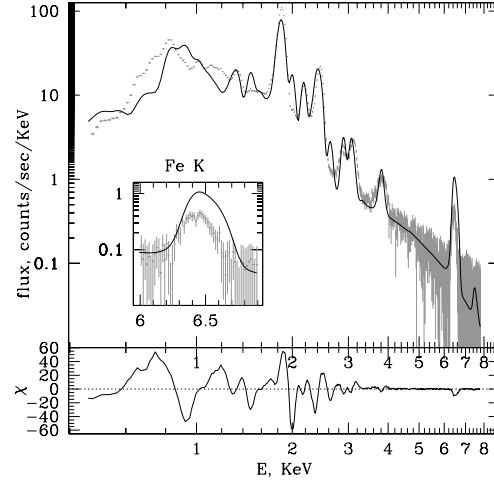


Figure 2. Observed (the gray crosses) and theoretical (the black solid line) spectra of the Tycho SNR. Inset shows Fe K_{α} line in details.

Table 1. The values of the best fit parameters for Tycho SNR model

$\rho_{\text{CSM}}, \text{g/cm}^{-3}$	q	C_{kill}	N_H, cm^{-2}
1.8×10^{-24}	0.93	0.0085	3.7×10^{21}

with the best-fitting interpolation parameters (Table 1). These profiles are very similar to the ones found in Decourchelle et al. (2001).

Using the model radial profile, the distance to the remnant was evaluated. Table 2 shows estimates of the distance to Tycho SNR as obtained from the X-ray flux normalization (column 2) and as derived from the brightness profiles (column 3). Also the value of distance to Tycho remnant from observed proper motion of filaments Smith et al. (1991) presented. The distance estimated from normalizations of the SNR spectrum is more than two times smaller than that derived from the brightness profiles. This may suggest that our model of Tycho SNR is underluminous.

Table 2. The estimates of the distance to Tycho SNR from W7 model, and estimates of the distance from (Smith et al. 1991)

flux	profiles	H_{α} filaments
$1.34 \pm 0.01 \text{ kpc}$	$3.1 \pm 0.1 \text{ kpc}$	$1.5 - 3.1 \text{ kpc}$

¹ http://xmm.vilspa.esa.es/external/xmm_data_acc/xsa/, obsID = 009621010

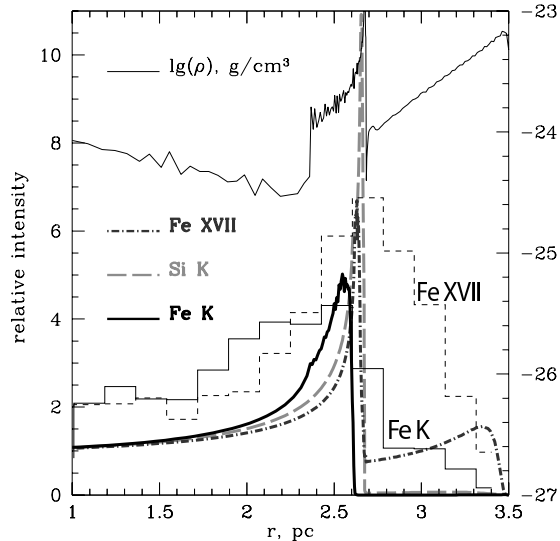


Figure 3. Simulated brightness profiles for the W7 model. The solid black line shows the density profile. Step-like profiles are observed by XMM-Newton, taken from Decourchelle et al. (2001): Fe K (solid line), Fe XVII (dashed line).

4 DISCUSSION

In this paper we have performed a hydrodynamical calculation of X-ray spectrum and radial brightness profiles in X-ray lines of SNR 1572 and compared the model X-ray emission with the XMM-Newton observations. We have used the classical deflagration model of thermonuclear supernova explosion W7 (Nomoto et al. 1984). We employed the method presented in Paper I and complemented by the inner-shell collisional ionization processes in the calculations of X-ray emission from the remnant. This improvement allowed us to remove discrepancies between theoretical and observational data found in Paper I.

We compared the model spectrum with the observable one by constructing the XSPEC table model with 3 interpolation parameters: q , C_{kill} , ρ_{CSM} . This model was used to fit observational data and to find the best-fitting values of the interpolation parameters. The moderate value of the parameter $C_{\text{kill}} \simeq 0.01$ and moderate value of the parameter $q \simeq 0.9$ suggest that thermal conduction is not very important and points to an appreciable non-Coulomb energy exchange between electron and ion components. These values also suggest the presence of magnetic field and plasma instabilities in the ejecta of the SNR.

The derived column density N_H is slightly smaller than that estimated earlier by Albinson et al. (1986), Smith et al. (1988), Itoh et al. (1988), Hwang et al.

(1998) and the value of ρ_{CSM} is higher than that derived by Decourchelle et al. (2001), Hughes (2000), Brinkman et al. (1998). Since it is not excluded that the W7 model is not the best one for the Tycho SNR, these parameters should be considered as zero approximation. In forthcoming studies we plan to examine other models with different modes of burning in type Ia supernovae with the goal to select the best-fitting one.

Estimations of the distance to the remnant using the X-ray flux normalization and remnant's angular size (Table 2) disagree likely due to neglecting the nonthermal component from the forward shock in X-ray emission modeling. Furthermore, probably the explosion model of Tycho supernova was more energetic than W7 model.

5 CONCLUSIONS

Our conclusions are as follows. The calculated X-ray spectrum and radial brightness profiles indicate that even the classical SN Ia deflagration model W7 is capable to reproduce the main observable features of a young SN Ia remnant, provided that all important physical processes are taken into account. In this case there is no need to introduce additional element mixing in the ejecta of this model (Itoh et al. 1988)

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